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Mathematics and Space Sciences

The Directorate of Mathematics and Space Sciences is responsible for basic research in mathematical and computer sciences and space sciences in the areas described in this section. Many critical research activities are multidisciplinary and involve support from the other scientific directorates within AFOSR. Such activities include joint research with the Directorate of Physics and Electronics in the design of high-power microwave devices, and joint research with the Directorate of Chemistry and Life Sciences in intelligent tutoring and information fusion. The control theory and mathematical modeling research supported by this directorate complements many structural, fluid mechanics, and propulsion research programs supported by the Directorate of Aerospace and Materials Sciences.

Dynamics and Control

This program is devoted to basic research in dynamics and control, leading to improved techniques
for the design and analysis of control systems with enhanced capabilities and performance for insertion into future Air Force systems. Proposals should include connectivity to appropriate Air Force air, space, and information system applications, which currently include advanced high-performance aircraft, unmanned aerial vehicles, missile systems, precision munitions, satellites, spacecraft, and command and control systems.

The Dynamics and Control program is interested in robust and adaptive feedback control concepts including: adaptive, reconfigurable flight control systems; guidance, navigation, and control of autonomous aerial vehicle systems and teams; image tracking and robust feedback control in high scintillation environments; control for rapid and precision targeting; active control of electromagnetic radiation by mastering the properties of a propagating surface; control and optimal design issues in aeroengines; control of fluid flow processes associated with aerospace vehicles; control using advanced airborne and space-borne sensors and actuators; and novel hybrid control systems that can intelligently manage actuator, sensor, and processor communications in complex, spatially distributed systems. The program emphasizes research in robust and adaptive multivariable feedback control applicable to nonlinear systems; constrained and receding horizon optimal control; novel approaches to system identification; integrated control and multidisciplinary design optimization; control of complex coupled fluid-structure systems; and, to a lesser degree, fundamental applied research in stochastic control, and control of discrete event dynamical systems. In general, support for research in linear systems theory is decreasing, while interest in control of complex, multi-scale, highly uncertain nonlinear systems is increasing.

Increased interest exists in the development of control concepts applicable to single and multiple unmanned aerial vehicles (UAVs) and micro air vehicles (MAVs). Areas of interest include cooperative/collaborative control of a team of UAVs conducting operations such as cooperative combat ISR, electronic attack, urban warfare, wide area search/attack, and persistent area denial. Real-time, adaptive acquisition, classification, prosecution and assessment of geographically dispersed targets is envisioned, requiring cooperation amongst UAVs such that critical timing constraints are satisfied for optimal performance. A cooperative decision and control theoretic framework is of interest to address robust dynamic control of distributed UAVs executing multiple, strongly coupled tasks with a high degree of decentralization.

A long-term goal of the Dynamics and Control program is control for intelligent autonomy, in order to achieve a higher level of autonomous control. The main features of autonomous control systems are determined by the need to solve complex optimization problems in the presence of uncertainty, in near real-time and without human intervention. Providing UAVs and MAVs with faculties of wide field-of-regard perception will be a significant step toward the realization of autonomous control, and in this area research in vision-based guidance, navigation and control is of interest.

The dramatic increase in complexity of Air Force systems provides unique challenges for the Dynamics and Control program. Meeting these challenges will require interdisciplinary approaches to provide significant advances in methods and tools for modeling, simulation, analysis, and real-time control of multi-scale, hybrid dynamical systems. In this regard, concepts motivated from studies of biological organisms and processes are of interest.

A new area of interest includes those dynamics and control problems related to laser communications systems. This area primarily deals with space-borne communications systems that must close dual control loops from single points to single points and multiple points to single points without accurate prior knowledge of other systems' positions and while in a dynamic environment. Specific areas of interest include pointing, acquisition and tracking control, on-board control system algorithms and ancillary vehicle control problems.

The Dynamics and Control program places special emphasis on techniques addressing realistic treatment of physical applications, to include attention to constraints, scalability, complexity management, handling of system variations and environmental uncertainty, and real-time operation in extreme and adversarial environments.

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Physical Mathematics and Applied Analysis

This program conducts research in physical mathematics and applied analysis to develop accurate models of physical phenomena to enhance the fidelity of simulation. It investigates the properties of coherently propagating ultrashort laser pulses (both the currently examined IR frequencies and possible extension to UV frequencies) through the air and their exploitation in areas such as electronic warfare (ancillary production of HPM), laser-guided munitions (possible propagation through obscurants), and irradiation of chem/bio clouds. It develops algorithms to simulate nonlinear optical effects within fiber lasers (with weaponization in mind) and nonlinear optical mediaand studies feasibility of designing reconfigurable warheads by suitable placement/timing of microdetonators as well as the operation of pulsed detonation engines. The program pursues description of the dynamics of internal stores released from transonic or supersonic platforms as well as the fluid dynamics accompanying curved, rotating jet turbine blades. Also, it pursues the dynamics of the atmosphere near and above the tropopause with an emphasis on the understanding of turbulence and its production by topography and storms is of interest. Other areas of interest include the understanding of chaos in circuitry such as missile guidance systems, prediction of effective properties of various composite media, advanced fracture mechanics theories, which also include thermal loading such as might be produced by exposure to a strong laser.

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Computational Mathematics

This program aims to develop improved mathematical methods and algorithms that exploit advanced computational capabilities in support of Air Force scientific computing interests. For the most part, this program seeks to develop innovative methods and algorithms that improve modeling and simulation capabilities. These improved capabilities, in turn, enable understanding, prediction, and control of complex physical phenomena crucial to the Air Force. These phenomena include fluid mechanics, plasma dynamics, electromagnetic wave generation, combustion processes, structural dynamics, control of large flexible structures, processing and performance of composite and tailored materials and crystal growth. Research in the computational mathematics program enables technological advances in aerodynamics, airbreathing propulsion, space propulsion, high-power microwaves, high-power lasers and structural mechanics. Research also supports the national program in high performance computing.

This program is developing numerical methods and algorithms to fully exploit the potential of high performance computers in calculating fast, accurate numerical solutions of complex systems occurring in both the design and operation of Air Force systems. Efficient use of available parallel machines requires that we pay increased attention to dynamic resource allocation and load balancing, domain decomposition techniques, scalable parallel algorithms, adaptive meshing, and parallel schemes for adaptive grid generation. As the cost of hardware continues to decrease, the results of this program may affect the design of specialized architectures for solving critical scientific problems.

Typically, the computational models in this program rely on some numerical scheme that implements a discretization of continuum mechanics equations--generally partial differential equations--that represent the physics of the particular problem. However, alternative computational models may be appropriate for some problems. To characterize the behavior of large, complex, real-world systems, we are examining modeling approaches that enable efficient, robust multidisciplinary design analysis and optimization. Overall, this program is investigating both traditional and radical approaches in this program. This program develops and improves a variety of numerical methods in this sub area, including finite difference methods, finite element methods, spectral methods, lattice gas algorithms, particle and vortex methods, essentially nonoscillatory methods and hybrid methods.

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Optimization and Discrete Mathematics

Our goal is to develop mathematical methods for solving large or complex problems, such as those occurring in logistics, target tracking, engineering design, and strategic planning. These problems can often be formulated as mathematical programs. Therefore, research is directed at new linear and nonlinear programming methods, especially when formulated for the solution of selected Air Force problems, and innovative techniques that combine the use of artificial intelligence and operations research. Tracking problems are often formulated as optimal filtering and estimation problems that require novel approaches to handling multiple targets in challenging environments.

This emphasis includes interaction between the collaborators, both human and machine. In addition, it will require new analytic techniques for development of robust plans under dynamic changes and uncertainty; that is, plans which perform well under a range of possible scenarios and can be changed to accommodate new conditions with minimal perturbation. This will enhance our existing research in robust optimization. In addition, modeling techniques to rapidly accommodate new information such as battle damage assessment and data fusion will be needed. These techniques should be designed to handle data that is possibly incomplete, conflicting, or overlapping. These models will view planning, execution, information acquisition, and replanning as a continuously evolving process.

Target tracking environments include multiple maneuvering targets in clutter, targets with low SNR, and cooperative tracking platforms. Computational complexity for real time applications is a key issue and competes with the need for accurate persistent tracks.

In addition to the evolution of traditional solution methods, the program supports new algorithmic paradigms (e.g., simulated annealing, genetic algorithms). Supported research includes discrete event systems, especially as it relates to Air Force transportation, target tracking, command and control systems, and battlefield management.

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Signals Communication and Surveillance

This research activity is concerned with the systematic analysis and interpretation of variable quantities that represent information, or convey information physically through a channel. Communications signals, enabling command and control, and surveillance images are of special importance. Signals are either naturally or deliberately generated and propagated by means of electromagnetic waves or other media, and are recaptured for use at a receiving sensor. Modern radar, infrared, and electro-optical sensing systems produce large quantities of raw signaling that exhibit hidden correlations, are distorted by noise, but still retain features tied to their particular physical origin. Statistical research that treats spatial and temporal dependencies in such data is necessary to exploit its usable information. An outstanding need in the treatment of signals is to develop resilient algorithms for data representation in fewer bits (compression), image reconstruction/enhancement, and spectral/frequency estimation in the presence of external corrupting factors. These factors can involve deliberate interference, noise, ground clutter, and multi-path effects. This AFOSR program maintains involvement with sophisticated mathematical methods, including time-frequency analysis and generalizations of the Fourier and wavelet transforms, that deal effectively with the degradation of signaling transmission across a channel. These methods hold promise in the detection and recognition of characteristic transient features, the synthesis of hard-to-intercept communications links, and the achievement of faithful compression and fast reconstruction for audio, video, and multi-spectral data. Continuous improvement in its repertoire of signal processing and statistical tools will enable the Air Force to maintain its lead in communications reach and air power projection, through responsive and cost-effective systems innovations.

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Software and Systems

The goal of this research program is to invest in the basic research needed to enable development of advanced computing science methods to support future Air Force needs in world-wide, 24-7 battlespace information management. Computing research is sought to meet several challenges including collection, control, and integration of the vast amounts of information flowing through battlespace information networks, protection of friendly information resources, and complexities in software and algorithm development in support of large information systems. Some specific areas of Infospheric Science research follow:

- Models of Information Flows
- Metrics for Information Flow
- Hierarchical Flow Models
- Information Dynamics
- Managing Massive Numbers of Triggers
- Information Pedigree/Certainty
- Stream data processing
- Automated Downgrading of Sensitive Information
- Preventing Self-Inflicted DoS Attacks
- Audit Data for Damage Assessment
- Steganography Detection
- Secure Code Composition
- Distributed, Assured Pipelines
- Application Layer Multicast Encryption
- Seamless Integration of Wireline-Wireless Networks
- Network monitoring, measurement, and inferencing
- Ad Hoc Wireless Networking
- Middleware
- Joint Battlespace Infosphere (JBI) System Stability
- Dynamic System Management
- JBI Information Metadata and Structure
- Evolvable Components

The need to collect, integrate, and disseminate information from widely disparate sources will be crucial in future military operations. Deep information extraction from all sources of data is a growing area of interest. For network protection, researchers will focus on determining and analyzing network security properties at all network layers and examining how to ensure that a network possesses these properties. New approaches to detection of intrusion, forensics, and an active response and recovery from an attack on information, are needed. Basic research that anticipates the nature of future information system attacks is critical to the survivability of these systems. Research on effective security policies across large, heterogeneous infospheres is of high interest. Techniques to automatically detect deceptive data or information are of interest. In the area of software and algorithm development, the program seeks mathematical approaches for the specification, design, and analysis of distributed software systems. Rigorous mathematical methods, especially those that involve aspects of timing, control, dependability, scalability and security, will be crucial to development of future battlespace infospheres. New approaches for overcoming the increasing computational complexity of these systems are essential.

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Artificial Intelligence

The timely management of information and the ability to make decisions based on that information is of paramount importance within this program. The key issue that is addressed is how to effectively incorporate all available information, from diverse sources and modalities, into the decision process. For example, mathematical foundations of information fusion must be established -- robust, integrated fusion architectures for handling increasing diversity of input sources are especially important. Information fusion, above the sensor level, to include situation refinement, impact assessment and process refinement is a major focus. Research is sponsored into how to make the best use of uncertain information; share and disseminate information; increase the accuracy, speed, and economy of the recognition and identification process; and aid the intelligence analyst.

The program concentrates on research needed to develop large-scale intelligent systems that can address practical Air Force needs. To that end, means are sought to scale up those methods that work for small knowledge-based systems. One goal is to overcome present limitations in the amount of knowledge used because of knowledge acquisition and management deficiencies. Present limitations on meaningful systems adaptation and system improvement with use also need to be overcome. Formalisms need to be developed for the representation of and reasoning with uncertainty, in handling corrupt information, identifying deceptive information, and effectively using experiences.

To aid the information analyst in fusing information from diverse modalities, we seek means to combine numeric and symbolic inference methods. Research could also focus on integrating probabilistic reasoning methods with traditional formal logic methods, and perhaps with other forms of computation. Qualitative methods that will drastically simplify computation and increase performance robustness are also of interest.

The program seeks to develop technology that will support decision-making. To that end, research is needed to develop intelligent agents capable of gathering information, reducing data to a manageable amount of essential information, and cooperating with other agents to solve problems. Research is also needed to combine artificial intelligence methods with operations research tools to overcome inefficiencies in solving some mission-critical Air Force problems (e.g., scheduling in a distributed, dynamic environment).

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Electromagnetics

Conduct research in electromagnetics to produce conceptual descriptions of electromagnetic properties of novel materials/composites (such as photonic band gap media) and simulate their uses in various operational settings. Evaluate methods to recognize (the inverse scattering problem) and track targets and to penetrate tree cover or other dispersive media with wide band radar (propagation of precursors for example) and design transmitters to produce such pulses. Develop computational electromagnetic simulation codes that are rapid and accompanied by rigorous error estimates/controls.

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Space Sciences

The AFOSR Space Sciences program seeks basic knowledge of the space environment to apply to the design and calibration of Air Force systems operating in and through space. For AFOSR purposes, the space environment begins at the base of the Earth's ionosphere, at an altitude of approximately 80 km (50 miles). Both the nominal and disturbed space environment can disrupt the detection and tracking of aircraft, missiles, satellites, and other targets, distort communications and navigation, and interfere with global command, control, and surveillance operations.

The physical and chemical behavior of the Earth's upper atmosphere affects the performance and longevity of Air Force systems operating in low-Earth orbit. Among other themes, AFOSR will consider research proposals related to:

- Ionospheric plasma turbulence and dynamics;
- Observing and modeling neutral winds, atmospheric tides, and gravity waves in the ionosphere;
- Variations in solar radiation received at Earth and their effects on satellite drag;
- Geomagnetic disturbances and their impacts on the ionosphere;
- Electron density structure and ionospheric scintillation; and
- Auroral and airglow evolution, as well as their spectroscopic emission signatures.

This program's goals are to improve the global specification and forecasting of the evolution of ionospheric irregularities and scintillation, to improve the specification of thermospheric dynamics and neutral densities, and to validate and enhance current ionospheric models using data assimilation techniques to improve operational forecasting and specification capability.

In the space environment well above low-Earth orbit, at geosynchronous orbit and beyond, phenomena such as solar eruptive events, variable interplanetary magnetic fields, solarelectromagnetic radiation, natural space debris, cosmic rays, geomagnetic storm enhancement of Earth's radiation belts, and interplanetary dust can degrade Air Force spacecraft and systems.

In this regime, research interests include, but are not limited to:

- The physics and chemistry of meteoroids, interplanetary dust, asteroids, and comets;
- The structure and dynamics of the solar interior and their role in driving solar eruptive activity;
- The mechanism(s) heating the solar corona and accelerating it outward as the solar wind;
- The triggers of coronal mass ejections (CMEs), solar energetic particles (SEPs), and solar

flares;
• The coupling between the solar wind, the magnetosphere, and the ionosphere;
• The origin and energization of magnetospheric plasma; and
• The triggering and temporal evolution of geomagnetic storms.

The ultimate AFOSR goal is to develop a predictive, global, coupled solar-terrestrial model that connects solar activity and output with the deposition of energy in the Earth's upper atmosphere, by specifying the flow of mass, momentum, and energy through interplanetary space, and by forecasting the turbulent plasma phenomena that mediate this flow.

The AFOSR Space Sciences program is also involved in advancing deep space surveillance techniques to observe and track Near Earth Objects and other physical threats to Air Force systems. In this regard, innovative astronomical detection and observation methods that involve advanced technology are also needed. Astrophysical or astronomical research and observations that investigate stellar-planetary interactions in general, and physical processes occurring in the Sun in particular, are also of interest.

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